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Influence of Sewage Sludge and Farmyard Manure Conjugated with RDF (NPK) on Yield and Economics of Green Gram (*Vigna radiata* L.) under *Zaid* Conditions

Mudit Tripathi [a], Ram Bharose [a], Harsh Kumar [a*], Rajnesh Kumar [a], Saumya [a], Ramesh Saini [b] S. L. Yadav [c] and Krishna Chahar [d]

[a] *Department of Soil Science and Agricultural Chemistry, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj- 211007, (U.P.), India.*
[b] *Department of Soil Science and Agricultural Chemistry, Suresh Gyan Vihar University, Jaipur India.*
[c] *Department of Soil Science and Agricultural Chemistry, R.V.S.K.V.V. Gwalior, Madhya Pradesh, India.*
[d] *Division of Soil Science and Agricultural Chemistry, Sher-e- Kashmir University of Agriculture Science and Technology, Jammu, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A field investigation was conducted during the *Zaid* seasons of 2023 and 2024 at the Research Farm of the Department of Soil Science and Agricultural Chemistry, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, India, to evaluate the effect of sewage sludge

**Corresponding author: E-mail: 0502harsh1998@gmail.com;*

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and farmyard manure (FYM) integrated with the recommended dose of fertilisers (RDF) on the yield and economics of green gram (*Vigna radiata* L.). The experiment was laid out in a factorial randomised block design (FRBD) with sixteen treatment combinations consisting of four levels of sewage sludge (0, 35, 70, and 105%) and four levels of FYM (0, 35, 70, and 105%) along with RDF. Each treatment was replicated three times. The experimental soil was sandy loam in texture with a pH of 6.89, low organic carbon (0.37%), low available nitrogen (238.31 kg ha^{-1}), medium available phosphorus (21.41 kg ha^{-1}), and medium available potassium (141.40 kg ha^{-1}). The green gram variety 'Star-444' was sown. The results revealed that integrated nutrient management significantly enhanced seed yield, straw yield, and economic returns over RDF alone. Among all treatments, the application of 105% sewage sludge + 105% FYM + RDF (T_{16}) produced the highest pooled seed yield (1356 kg ha^{-1}), straw yield (2561 kg ha^{-1}), gross return (₹123,709 ha^{-1}), net return (₹70,455 ha^{-1}), and benefit–cost ratio (2.32). The study demonstrated that the combined application of sewage sludge and FYM with RDF considerably improved crop productivity and profitability through enhanced nutrient availability, improved soil physical conditions, and sustained nutrient release.

Keywords: Yield; economics; zaid season; sewage sludge; FYM; NPK; green gram.

1. Introduction

Green gram (*Vigna radiata* L. Wilczek), commonly known as mung bean, is one of the most important pulse crops cultivated in tropical and subtropical regions of the world. It is valued for its short duration, high nutritional quality, adaptability to diverse agro-climatic conditions, and ability to fix atmospheric nitrogen through symbiosis with *Rhizobium*. Green gram seeds contain approximately 22–26% protein, 60–65% carbohydrates, essential amino acids, dietary fibre, vitamins, and minerals, making the crop an important source of affordable protein for vegetarian populations. Besides its nutritional significance, green gram improves soil fertility by contributing biologically fixed nitrogen and crop residues, making it an integral component of sustainable cropping systems (Sahu *et al.,* 2021; Sudhakaran & Bukkan, 2021). India is the world's largest producer and consumer of pulses, and green gram occupies a prominent position among pulse crops because of its wide adaptability and economic importance. Despite the substantial area under cultivation, the productivity of green gram remains below its genetic potential due to poor soil fertility, declining organic matter, imbalanced fertiliser application, micronutrient deficiencies, erratic rainfall, and inadequate adoption of improved nutrient management practices. The depletion of soil organic carbon caused by continuous cultivation and excessive dependence on chemical fertilisers has emerged as a major constraint to sustainable pulse production. Consequently, improving nutrient-use efficiency while maintaining soil health has become a priority for sustainable agriculture. Integrated Nutrient Management (INM) has been recognised as an effective strategy to sustain crop productivity while preserving soil quality (Mahajan *et al.,* 2008; Dhakal *et al.,* 2016; Meena *et al.,* 2016). INM emphasises the balanced use of inorganic fertilisers together with organic manures and biofertilisers to provide an adequate and continuous supply of nutrients throughout the crop growth period. The combined use of these nutrient sources enhances nutrient-use efficiency, improves soil physical, chemical, and biological properties, stimulates microbial activity, and reduces nutrient losses through leaching and volatilisation. Long-term adoption of INM also contributes to increased soil organic carbon, improved aggregation, greater water-holding capacity, and enhanced nutrient cycling, ultimately leading to sustainable crop production (Meena *et al.,* 2016). Among the organic nutrient sources available for crop production, farmyard manure (FYM) remains one of the most widely used because of its ability to improve soil fertility and crop productivity. FYM supplies essential macro- and micronutrients in addition to increasing soil organic matter. Its gradual decomposition ensures sustained nutrient release during the crop growth period, while simultaneously improving soil structure, aeration, infiltration, moisture retention, and cation exchange capacity. Enhanced microbial activity resulting from FYM application accelerates nutrient mineralisation and improves nutrient availability to plants, thereby promoting vigorous vegetative growth and higher yield (Dhakal *et al.,* 2016; Kumar *et al.,* 2024). Sewage sludge has recently gained attention as a valuable organic amendment owing to its high content of organic matter and plant nutrients, particularly nitrogen and phosphorus. When properly treated and applied within recommended limits, sewage sludge can serve as an effective alternative nutrient source while simultaneously providing an environmentally sound method for recycling municipal waste. Application of treated sewage sludge increases soil organic carbon, microbial biomass, aggregate stability, and nutrient availability, thereby improving crop productivity. Recycling sewage sludge in agriculture also supports the principles of a circular economy by converting urban waste into a useful agricultural input (Verma *et al.*, 2021). The combined application of sewage sludge and FYM has the potential to produce synergistic effects on soil fertility and crop growth. While sewage sludge provides relatively higher concentrations of readily available nutrients, FYM enhances microbial activity and improves nutrient mineralisation, resulting in a more synchronised nutrient supply throughout the crop growth cycle (Lakshman *et al.*, 2023). Their combined use also minimises nutrient losses, improves root development, increases biological nitrogen fixation, and enhances photosynthetic efficiency, leading to greater biomass accumulation and seed production. Green gram responds favourably to balanced nutrient management because of its relatively short growth duration and high nutrient demand during flowering and pod development (Kumar *et al.*, 2024). Adequate nutrient availability during these critical stages improves nodulation, chlorophyll synthesis, enzyme activity, photosynthesis, dry matter accumulation, pod formation, and seed filling. Meena *et al.* (2016) reported that the combined application of FYM, *Rhizobium*, and recommended fertilisers significantly enhanced growth and yield of green gram compared with the sole application of inorganic fertilisers. Economic sustainability is equally important for the successful adoption of nutrient management practices. Farmers are more likely to adopt technologies that provide higher profitability in addition to increased productivity (Tyagi *et al.,* 2014; Singh *et al.,* 2019). Therefore, assessment of gross returns, net returns, and benefit–cost ratio is essential for identifying economically viable nutrient management strategies. Integrated use of organic manures with mineral fertilisers not only improves crop yield but also enhances input-use efficiency, resulting in higher profitability and long-term sustainability.

Recent evidence further supports the judicious integration of organic and mineral nutrient sources. In green gram, the combined use of mineral fertilisers, organic amendments and microbial inputs has been associated with improved soil properties and crop performance (Sarkar *et al.*, 2023), while soil-test-based integration of FYM and mineral fertilisers has enabled targeted nutrient management in mungbean (Isha *et al.*, 2024). Evidence from another crop also indicates that combining organic and inorganic nutrient sources can improve growth and yield performance relative to the sole use of individual nutrient sources (Prajapati *et al.*, 2026). Long-term research on sewage-sludge recycling further indicates that suitably treated or composted sludge can improve soil biological quality and crop productivity, although its agricultural use requires appropriate treatment and safeguards against contaminants (Li *et al.*, 2024; Riaz *et al.*, 2025).

However, evidence remains limited within the context of this manuscript regarding the combined effects of graded sewage-sludge and FYM levels, applied with the recommended dose of fertilisers, on both the yield and economic performance of green gram under Zaid conditions at Prayagraj. A comparative assessment across two consecutive seasons is therefore required to identify a treatment combination that improves crop productivity while maintaining economic viability.

Accordingly, the present study aimed to evaluate the individual and combined effects of graded sewage-sludge and FYM levels applied with the recommended dose of NPK fertilisers on seed yield, straw yield, gross return, net return and benefit–cost ratio of green gram during the Zaid seasons of 2023 and 2024.

2. Materials and Methods

The field experiment was conducted during the *Zaid* seasons of 2023 and 2024 at the Research Farm of the Department of Soil Science and Agricultural Chemistry, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh, India, situated in the Indo-Gangetic alluvial plains under a subtropical climate characterised by hot summers, mild winters, and an average annual rainfall of approximately 1100 mm, most of which is received during the southwest monsoon. Prior to the initiation of the experiment, representative surface soil samples were collected from the experimental field and analysed using standard laboratory procedures. The experimental soil was sandy loam in texture, slightly acidic to neutral in reaction (pH 6.89), low in organic carbon (0.37%) and available nitrogen (238.31 kg ha^{-1}), and medium in available phosphorus (21.41 kg ha^{-1}) and available potassium (141.40 kg ha^{-1}). The experiment was laid out in a Factorial Randomised Block Design (FRBD) comprising sixteen treatment combinations involving four levels of sewage sludge (0, 35, 70, and 105%) and four levels of farmyard manure (FYM) (0, 35, 70, and 105%), corresponding to doses of 0, 7, 14, and 21 t ha^{-1}both SS and FYM, respectively; these were integrated with the recommended dose of NPK fertilisers (RDF). Each treatment combination was replicated three times. The green gram variety 'Star-444' (*Vigna radiata* L.) was used as the test crop because of its suitability to the agro-climatic conditions of the region. Sewage sludge and FYM were incorporated into the soil according to the respective treatment combinations before sowing, while the recommended dose of NPK fertilisers was applied uniformly to all plots. All recommended agronomic practices, including irrigation, intercultural operations, weed management, and plant protection measures, were followed uniformly throughout the crop growth period to ensure optimum crop development and minimise experimental variability. The crop was harvested at physiological maturity, and observations on seed yield (kg ha^{-1}), straw yield (kg ha^{-1}), gross return (₹ ha^{-1}), net return (₹ ha^{-1}), and benefit–cost ratio were recorded. Gross return was estimated based on the prevailing market prices of the produce; net return was calculated by subtracting the total cost of cultivation from the gross return; and the benefit–cost ratio was determined by dividing the gross return by the total cost of cultivation. The data generated during both years were subjected to analysis of variance (ANOVA) appropriate for the Factorial Randomised Block Design, and treatment means were compared at the 5% level of significance. The standard error of the mean (SEm±) and critical difference (CD) values were computed wherever the treatment effects were significant, and pooled analysis over the two experimental years was carried out to evaluate the consistency of treatment performance.

3. Results and Discussion

The data presented in Table 1 and Fig. 1 clearly show that the combined application of sewage sludge and farmyard manure (FYM), together with the recommended dose of fertilisers (RDF), significantly enhanced the yield and economic performance of green gram during both experimental years and in the pooled analysis.

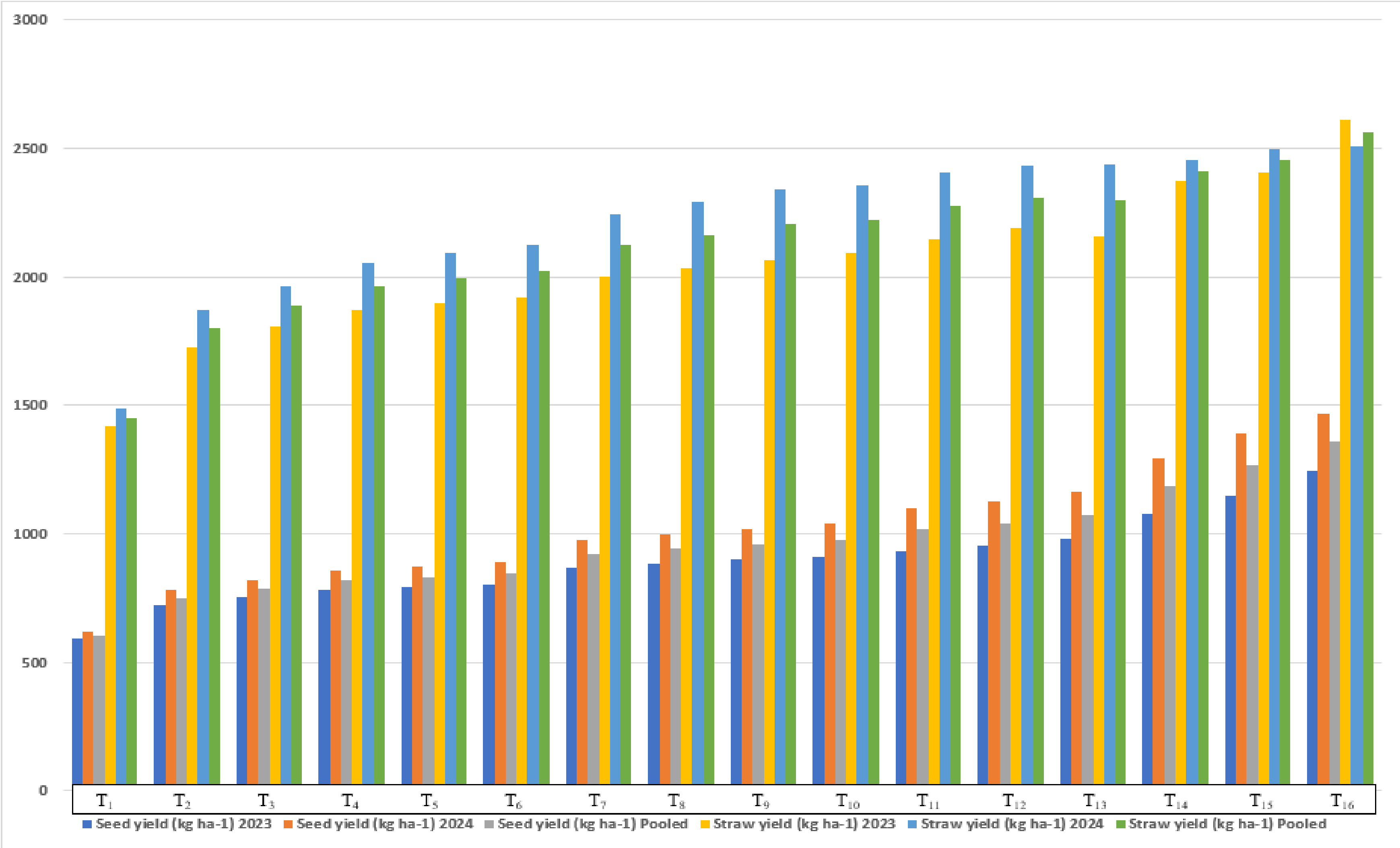
3.1 Effect of Sewage Sludge and FYM Combined with NPK on the Yield of Green Gram

Seed yield exhibited a consistent increasing trend with increasing levels of sewage sludge and FYM, indicating the beneficial effect of integrated nutrient management on crop productivity. The significant variation among treatments was evident from the calculated critical difference (CD) values of 44.62 kg ha-1, 51.64 kg ha-1, and 48.13 kg ha-1 during 2023, 2024, and the pooled analysis, respectively. During the first experimental year (2023), seed yield ranged from 591 kg ha^{-1} under T_1 (0% sewage sludge + 0% FYM + RDF) to 1244 kg ha^{-1} under T_{16} (105% sewage sludge + 105% FYM + RDF). During 2024, the seed yield varied from 619 kg ha^{-1} to 1468 kg ha^{-1} under the same treatments. The pooled mean revealed that seed yield increased from 605 kg ha^{-1} under the control treatment to 1356 kg ha^{-1} under T_{16}, showing an improvement of approximately 124.13% over RDF alone. Among all treatments, T_{16} recorded the highest seed yield, followed by T_{15} (1266 kg ha^{-1}), T_{14} (1185 kg ha^{-1}), and T_{13} (1071 kg ha^{-1}), demonstrating the superiority of higher organic amendment levels combined with inorganic fertilisers. These favourable soil conditions promoted greater nodulation, efficient nutrient uptake, and enhanced photosynthetic activity, ultimately leading to higher seed production. Similar results were reported by Kumar *et al.* (2024), who found that the residual application of FYM integrated with the recommended dose of fertilisers significantly improved growth, yield attributes, seed yield, stover yield, nutrient uptake, soil organic carbon, and available nutrient status in a mustard–green gram cropping system. Similarly, Singh *et al.* (2019) reported that integrated application of farmyard manure, biofertilisers, and inorganic fertilisers significantly enhanced yield attributes, nutrient uptake, and grain yield of green gram compared with the sole application of chemical fertilisers, highlighting the importance of integrated nutrient management for sustaining crop productivity.

A continuous increase in straw yield was observed with increasing levels of sewage sludge and FYM, indicating that integrated nutrient management improved vegetative growth and total biomass production of the crop. The significant treatment effects were confirmed by the critical difference values of 100.93 kg ha-1, 111.17 kg ha-1, and 106.02 kg ha-1 during 2023, 2024, and the pooled analysis, respectively. During 2023, straw yield ranged from 1417 kg ha^{-1} under T_1 (0% sewage sludge + 0% FYM + RDF) to 2612 kg ha^{-1} under T_{16} (105% sewage sludge + 105% FYM + RDF). During 2024, straw yield varied from 1486 kg ha^{-1} under the control treatment to 2510 kg ha^{-1} under T_{16}. The pooled analysis revealed that straw yield increased from 1452 kg ha^{-1} in T_1 to 2561 kg ha^{-1} in T_{16}, representing an improvement of approximately 76.4% over RDF alone. Among all treatments, T_{16} recorded the highest pooled straw yield (2561 kg ha^{-1}), followed by T_{15} (2451 kg ha^{-1}), T_{14} (2413 kg ha^{-1}), and T_{12} (2310 kg ha^{-1}). The lowest straw production was observed under T_1, where only RDF was applied. The higher biomass production under integrated nutrient management treatments indicates that organic amendments enhanced nutrient availability and improved soil conditions, resulting in better vegetative growth. These improvements promoted vigorous vegetative growth and greater dry matter accumulation, leading to higher straw yield. Similar findings were reported by Singh *et al.* (2019), who observed significantly higher seed and straw yields of green gram under integrated nutrient management involving organic manures, biofertilisers, and chemical fertilisers. Likewise, Lakshman *et al.* (2023) reported that the combined application of vermicompost, *Rhizobium*, and Bio-NPK consortium significantly enhanced dry matter accumulation, biological yield, and straw yield of green gram compared with the sole application of inorganic fertilisers. These findings corroborate the present results and emphasise the beneficial role of integrated nutrient management in enhancing biomass production in pulse crops.

Table 1. Effect of sewage sludge and FYM conjugated with NPK on yield and economics of green gram in *Zaid* seasons of 2023, 2024 and pooled

Treatment	Seed yield (kg ha^{-1})			Straw yield (kg ha^{-1})			Gross return (₹/ha)			Net return (₹/ha)			B:C Ratio		
	2023	**2024**	**Pooled**	**2023**	**2024**	**Pooled**	**2023**	**2024**	**Pooled**	**2023**	**2024**	**Pooled**	**2023**	**2024**	**Pooled**
T_1: SS 0 % + FYM @ 0 % + (RDF)	591	619	605	1417	1486	1452	54082	57928	56005	15086	16457	15771	1.39	1.40	1.39
T_2: SS 0 % + FYM @ 35 % + (RDF)	720	779	750	1727	1871	1799	65901	72911	69406	24945	29410	27177	1.61	1.68	1.64
T_3 : SS 0 % + FYM @ 70 % + (RDF)	752	819	785	1805	1965	1885	68871	76586	72729	25955	31055	28505	1.60	1.68	1.64
T_4: SS 0 % + FYM @ 105 % + (RDF)	779	856	817	1870	2053	1962	71344	80033	75688	26468	32472	29470	1.59	1.68	1.64
T_5: SS 35 % + FYM @ 0 % + (RDF)	790	872	831	1897	2092	1994	72369	81542	76956	31063	37691	34377	1.75	1.86	1.81
T_6: SS 35 % + FYM @ 35 % + (RDF)	800	886	843	1921	2127	2024	73301	82910	78106	30035	37029	33532	1.69	1.81	1.75
T_7: SS 35 % + FYM @ 70 % + (RDF)	869	976	923	2000	2245	2122	79410	91028	85219	34184	43117	38650	1.76	1.90	1.83
T_8: SS 35 % + FYM @ 105 % + (RDF)	883	996	940	2030	2292	2161	80616	92932	86774	33430	42991	38210	1.71	1.86	1.78
T_9: SS 70 % + FYM @ 0 % + (RDF)	898	1018	958	2065	2342	2204	82011	94973	88492	38395	48742	43569	1.88	2.05	1.97
T_{10}: SS 70 % + FYM @ 35 % + (RDF)	909	1037	973	2092	2354	2223	83059	96639	89849	37483	48378	42930	1.82	2.00	1.91
T_{11}: SS 70 % + FYM @ 70 % + (RDF)	933	1098	1016	2147	2405	2276	85241	102091	93666	37705	51800	44752	1.79	2.03	1.91
T_{12}: SS 70 % + FYM @ 105 % + (RDF)	952	1125	1039	2190	2430	2310	86972	104486	95729	37476	52165	44821	1.76	2.00	1.88
T_{13}: SS 105 % + FYM @ 0 % + (RDF)	980	1162	1071	2155	2440	2298	89227	107710	98469	43301	59099	51200	1.94	2.22	2.08
T_{14}: SS 105 % + FYM @ 35 % + (RDF)	1078	1291	1185	2372	2453	2413	98213	118966	108590	50327	68325	59326	2.05	2.35	2.20
T_{15}: SS 105 % + FYM @ 70 % + (RDF)	1145	1388	1266	2404	2498	2451	103979	127503	115741	54133	74832	64483	2.09	2.42	2.25
T_{16}: SS 105 % + FYM @ 105 % + (RDF)	1244	1468	1356	2612	2510	2561	112955	134463	123709	61149	79762	70455	2.18	2.46	2.32
SEm+	**15.45**	**17.88**	**16.66**	**34.94**	**38.49**	**36.71**	-	-	-	-	-	-	-	-	-
CD at 5%	**44.62**	**51.64**	**48.13**	**100.93**	**111.17**	**106.02**	-	-	-	-	-	-	-	-	-


3000
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2000
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T1 T2 T3 T4 T5 T6 T7 T8 T9 T10 T11 T12 T13 T14 T15 T16
Seed yield (kg ha-1) 2023
Seed yield (kg ha-1) 2024
Seed yield (kg ha-1) Pooled
Straw yield (kg ha-1) 2023
Straw yield (kg ha-1) 2024
Straw yield (kg ha-1) Pooled

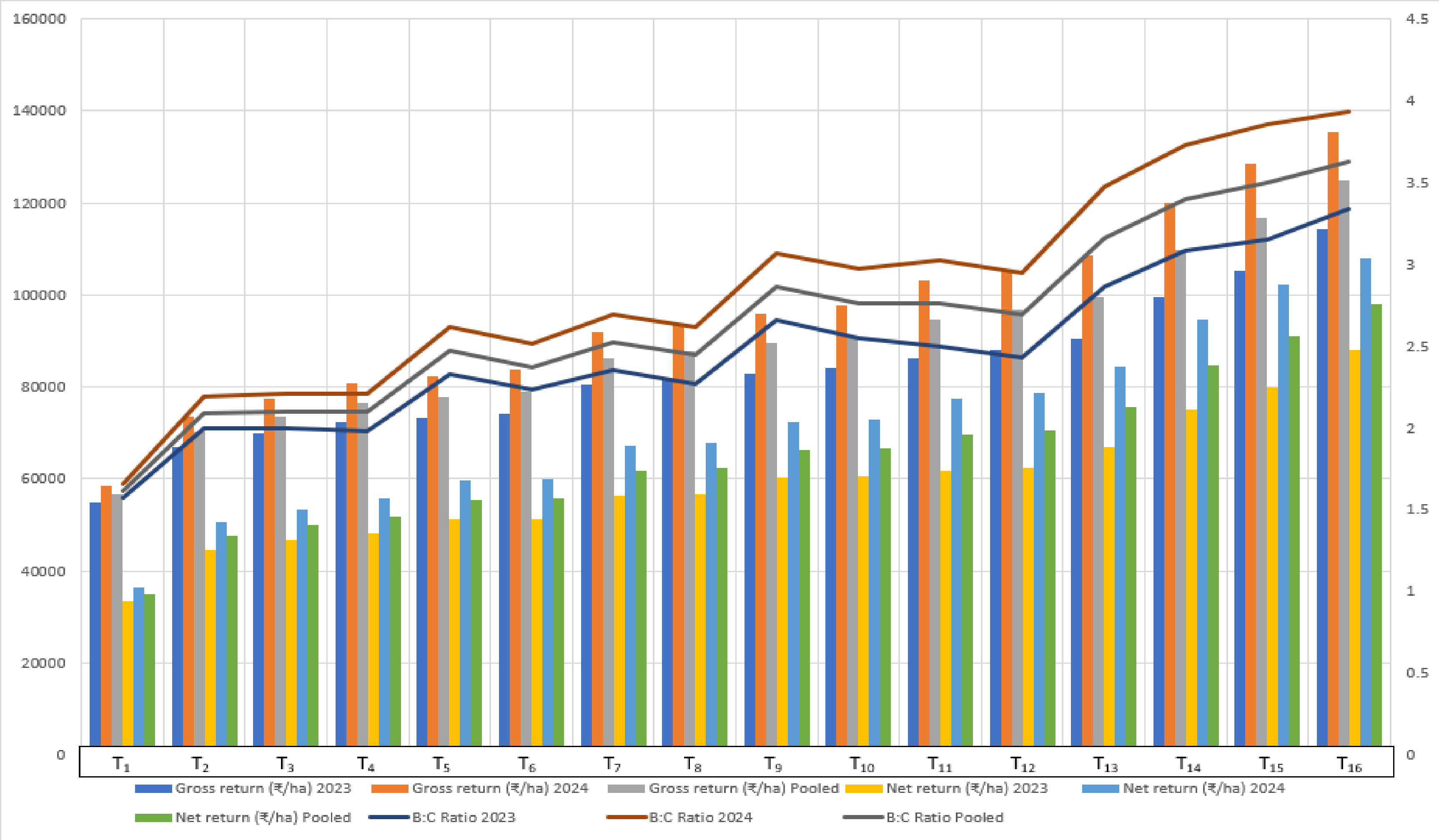

Fig. 1. Graph showing Effect of sewage sludge and FYM conjugated with NPK on yield and economics of green gram in *Zaid* seasons of 2023, 2024 and pooled

3.2 Economics of Different Treatments

Gross return increased progressively with increasing levels of sewage sludge and FYM during both years of experimentation as well as in the pooled analysis (Table 1), reflecting the positive effect of integrated nutrient management on crop productivity and market value. During the *Zaid* season of 2023, gross return varied from ₹54,082 ha^{-1} under the control treatment (T_1: 0% sewage sludge + 0% FYM + RDF) to ₹112,955 ha^{-1} under T_{16} (105% sewage sludge + 105% FYM + RDF). Likewise, during 2024, gross return increased from ₹57,928 ha^{-1} to ₹134,463 ha^{-1}, whereas the pooled gross return ranged from ₹56,005 ha^{-1} under T_1 to ₹123,709 ha^{-1} under T_{16}. Treatments T_{15} and T_{14} also recorded considerably higher pooled gross returns of ₹115,741 ha-1 and ₹108,590 ha-1, respectively. The substantial increase in gross return under integrated nutrient management was mainly due to higher seed and straw yields obtained from the combined application of sewage sludge and FYM. Meena *et al.* (2016) reported significantly higher gross returns in green gram with integrated application of FYM and recommended fertilisers compared with the sole application of inorganic fertilisers. Similarly, Mohit and Kumar (2022) observed that the integration of vermicompost, biofertilisers, and RDF significantly enhanced gross returns owing to higher grain and straw yields. Comparable results were also reported by Kumar *et al.* (2024), who found that integrated nutrient management increased biological yield and gross monetary returns in green gram.

Net return followed a trend similar to gross return and increased significantly with increasing levels of sewage sludge and FYM. During 2023, net return ranged from ₹15,086 ha^{-1} under the control treatment to ₹61,149 ha^{-1} under T_{16}. During 2024, it increased from ₹16,457 ha^{-1} to ₹79,762 ha^{-1}, while the pooled net return varied from ₹15,771 ha^{-1} to ₹70,455 ha^{-1}. Among all treatments, T_{16} recorded the highest pooled net return (₹70,455 ha^{-1}), followed by T_{15} (₹64,483 ha^{-1}), T14 (₹59,326 ha-1), and T13 (₹51,200 ha^{-1}). Compared with the control, T_{16} increased pooled net return by approximately 346.7%, demonstrating the economic advantage of integrating organic and inorganic nutrient sources. The pooled B:C ratio varied from 1.39 under the control treatment to 2.32 under T_{16}. During 2023, the highest B:C ratio was 2.18, whereas during 2024 it further increased to 2.46 under the same treatment. Treatments T_{15} (2.25 pooled), T_{14} (2.20 pooled) and T_{13} (2.08 pooled) also recorded higher B:C ratios compared with other treatment combinations. The higher B:C ratio under T_{16} indicates that every unit of investment generated substantially greater economic returns than the control. This improvement resulted from increased productivity combined with efficient utilisation of nutrients supplied through sewage sludge, FYM and RDF. Organic amendments improved nutrient availability and soil fertility, while chemical fertilisers ensured immediate nutrient supply during the early growth stages, together resulting in higher input-use efficiency and profitability. The present findings are in close agreement with Meena *et al.* (2013), Pal *et al.* (2016), and Verma *et al.* (2021), all of whom reported significantly higher benefit–cost ratios under integrated nutrient management compared with the sole application of chemical fertilisers.

4. Conclusion

The study clearly demonstrates that integrated application of sewage sludge and farmyard manure (FYM) combined with the recommended dose of NPK fertilisers significantly enhanced the productivity and profitability of green gram (*Vigna radiata* L.) during the *Zaid* seasons of 2023 and 2024. The combined application of organic and inorganic nutrient sources showed a clear positive influence on seed yield, straw yield, and economic performance compared with RDF alone. Among all treatment combinations, the application of sewage sludge @ 105% + FYM @ 105% along with RDF (T_{16}) was the best-performing treatment, recording the highest seed yield (1244, 1468, and 1356 kg ha-1 during 2023, 2024, and the pooled analysis, respectively) and straw yield (2612, 2510, and 2561 kg ha-1, respectively). The superior performance of T_{16} was attributed to the complementary effects of sewage sludge and FYM, which improved soil organic matter status, nutrient availability, microbial activity, soil physical properties, and nutrient-use efficiency. Sewage sludge supplied essential macro- and micronutrients, whereas FYM enhanced nutrient mineralisation, soil aggregation, moisture retention, and biological activity, creating a favourable environment for better root development, nodulation, vegetative growth, and seed formation. The integrated nutrient management approach also showed economic benefits. Treatment T_{16} recorded the highest gross return (₹112,955, ₹134,463, and ₹123,709 ha^{-1}), net return (₹61,149, ₹79,762, and ₹70,455 ha-1) and benefit-cost ratio (2.18, 2.46, and 2.32) during 2023, 2024, and the pooled analysis, respectively. Compared with RDF alone, the combined application of sewage sludge and FYM resulted in substantial improvement in profitability, demonstrating the economic feasibility of organic resource recycling in green gram production. Under the conditions of this study, the application of 105% sewage sludge + 105% FYM along with RDF was the best-performing nutrient-management treatment for improving the yield and economic returns of green gram in Prayagraj, Uttar Pradesh. This integrated approach may contribute to sustainable pulse production by improving nutrient-use efficiency, recycling organic wastes, reducing dependence on chemical fertilisers, and maintaining long-term soil productivity.

5. Limitations

The study was conducted over two Zaid seasons at one location using a single green gram variety; therefore, the findings are specific to the experimental soil, climate, and management conditions. Economic estimates were based on the prevailing input and output prices during the study period. The experiment assessed yield and profitability but did not establish the long-term effects of repeated sewage-sludge application. Multi-location and longer-term validation is therefore required before broad recommendation of the highest-performing treatment.

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Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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